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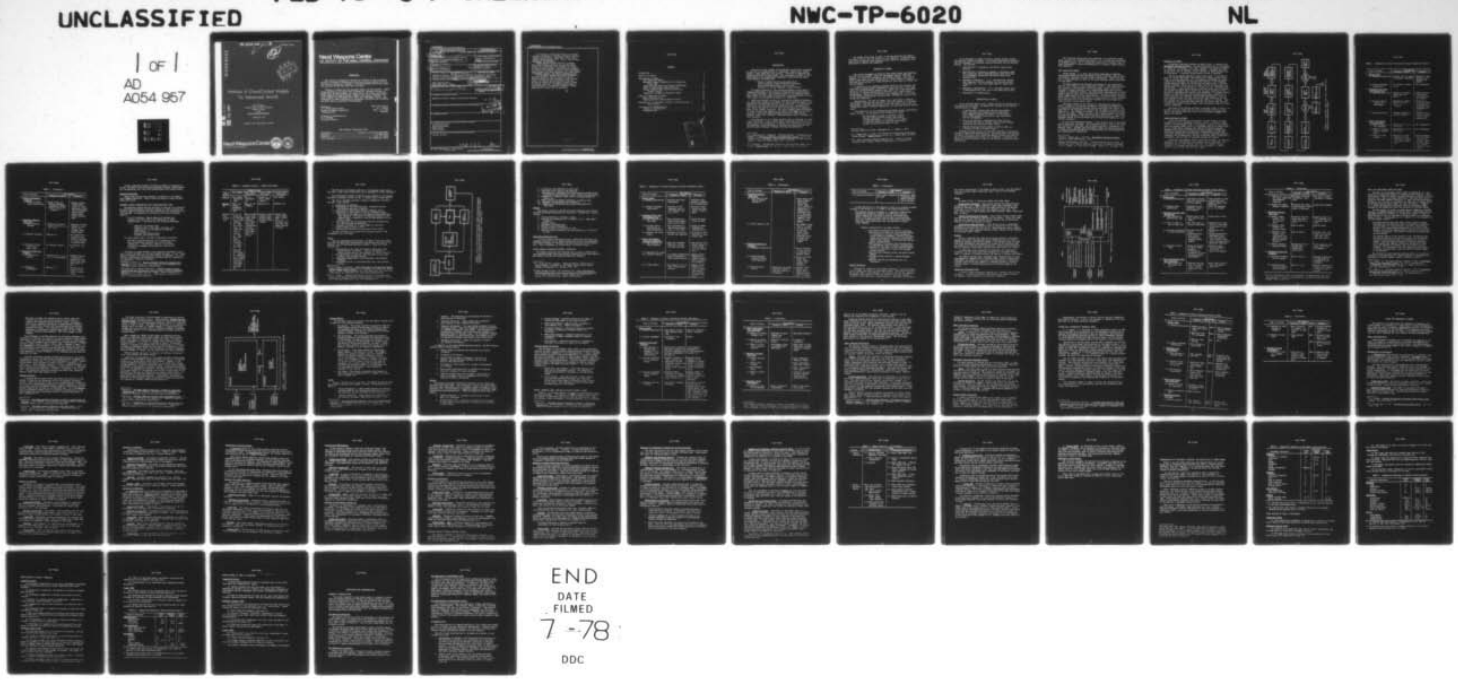

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Analysis of Crew/Cockpit Models for Advanced Aircraft

by
Charles P. Greening
Autonetics Division, Rockwell International
Anaheim, California
for the
Systems Development Department

FEBRUARY 1978

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FOREWORD

This review of mathematical models was conducted by the Autonetics Division of Rockwell International under Navy contract N00123-74-C-0236. The work was supported by AirTask No. A003P-3400/008B/7F55-525-000 under the direction of CDR Paul Chatelier (AIR 340F).

Ronald A. Erickson was the technical monitor on the contract. Appropriate portions of the report were reviewed for technical accuracy by George Sepp, Richard Hanking, and Joseph Burke, the Vought Corporation; Richard Edwards, Boeing Aerospace Company; Carl Asiala, McDonnell Aircraft Company; and CDR Norman Lane, Naval Air Development Center. The cooperation of these individuals in furnishing information and reviewing the draft report is gratefully acknowledged.

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7 February 1978

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(U) *Analysis of Crew/Cockpit Models for Advanced Aircraft*, by Charles P. Greening, Autonetics Division, Rockwell International. China Lake, Calif., Naval Weapons Center, February 1978. 58 pp. (NWC TP 6020, publication UNCLASSIFIED.)

(U) The purpose of this study was to examine five active computer models of the aircrew/cockpit system, and to determine their relevance to current and future attack aircraft. The models were compared in terms of their general structure, input requirements, output options, and their sensitivity to a wide variety of equipment, mission, and operator characteristics.

(U) The models reviewed are similar in several important respects: They all require a detailed mission scenario and task analysis to steer the simulation; all require data on performance time and accuracy as inputs; and all generate outputs related to operator task load. The models differ widely in their sensitivity to significant variables. Recommendations for future work are presented.

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CONTENTS

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INTRODUCTION

Advanced aircraft systems are increasingly placing the crew member in the role of a system monitor or supervisor, rather than a simple detector, power amplifier, and actuator. This kind of assertion has become a platitude in recent years. But as recently as March of 1976, participants in an international symposium on monitoring and supervisory behavior concluded that

> "Models of human monitoring and supervisory control behavior, human information processing and decision-making exist, but are often primitive or not well matched to applications."[1]

The papers presented at that symposium present a broad range of suggested approaches to the problem of modeling these characteristically human processes. The stunning variety of the approaches gives some insight into the degree of uncertainty among specialists as to the "best" model of the operator-as-monitor or -supervisor.

There are basically two ways to approach the problem of modeling the crew/cockpit system in the absence of widely accepted models of the supervisory or monitoring portions of the crew task: (1) model those portions we can, and hope that the omissions and/or approximations don't matter too much or (2) wait until we can settle on an adequate model of the "higher" functions. The choice between these alternatives is often forced by the urgency of the need to have some kind of model operating - especially among designers/producers of new aircraft systems. Hence, the "finished," operating models tend to represent the first approach.

The situation is, in a sense, parallel with the modeling of visual target acquisition. Most of those models emphasize such functions as visual acuity and the detection of objects in a featureless or cluttered background, while minimizing or omitting such activities and variables as search strategy, training, briefing and experience.[2]

---

[1] T.B. Sheridan and G. Johannsen. "Workshop Reports. Introduction and Summary" in Monitoring Behavior and Supervisory Control, ed. by T.B. Sheridan and G. Johannsen. NATO Conference Series, III Human Factors, Volume 1. New York, Plenum Press, 1976. pp 473-77.

[2] C.P. Greening. "Mathematical Modeling of Air-to-Ground Target Acquisition," Human Factors, Vol. 18, No. 2 (April 1976), pp 111-148.

The reader should bear in mind, in the descriptions and comparisons which follow, that the authors of the completed, documented models have perforce modeled those characteristics which are understood, and simplified or omitted the remainder.

SELECTION OF MODELS

The current Statement of Work for this study listed four modeling efforts to be included[3]: Naval Air Development Center; McDonnell Douglas, St. Louis; LTV Aerospace; and Boeing, Seattle. All four of those listed have provided documentation on their respective models. The descriptive material in later sections of this report is based upon those documents.

In addition to the modeling programs listed in the contract, two other major programs appear frequently in the literature: the SAINT effort at the Aero-Medical Research Lab, WPAFB; and a long-term modeling effort at Applied Psychological Services, Inc., under various sponsorships. These two efforts were also examined and, in the case of the Applied Psychological Services work, included as a part of the review and comparison.

Historically, the work of Siegel, Wolf, and others at Applied Psychological Services has influenced the other efforts to a considerable extent. The 1961 description of what has come to be called the "Siegel-Wolf model"[4] predates essentially all the other work by several years.

The SAINT work is not reviewed because SAINT is not a man/cockpit model, as such. In the words of the custodian of SAINT[5]

> "Our philosophy has been to develop a fairly general modeling method rather than promote a single man-model.....we believe it is useful to provide a method for building these models without dictating which model to use."

---

[3]Contract N00123-74-C-0236, Supplement No. 6, August 1, 1976.

[4]A.I. Siegel and J.J. Wolf, "A Technique for Evaluating Man/Machine System Designs," Human Factors, Vol 3, No. 1 (March 1961) pp 18-28.

[5]G.P. Chubb (Aerospace Medical Research Lab). Letter to Ronald Erickson (NWC), subject "SAINT Documentation," 24 January 1977.

In the selection of models for study, several general criteria were applied, though not rigidly. The criteria were either implied in the work statement, or developed during discussions with the contract monitor. They include:

1. Applicability to integrated, interactive displays and controls.
2. Applicability to discrete as opposed to continuous tasks. (The continuous control modeling efforts have given rise to a voluminous, specialized literature which is not examined here.)
3. Reasonable "complexity." (i.e., The model must address task sequences, multiple displays and controls, mission conditions, etc., not just single tasks or lumped task load.)
4. Reasonable "completeness." (i.e., The model should exist in near-usable form - not just a flow chart and an idea.)
5. Availability of documentation.

DESCRIPTIONS OF MODELS

In the following pages, brief, largely qualitative descriptions of five models will be found. The models will be seen to have several characteristics in common:

1. A scenario and a related task analysis are assumed to exist, providing the framework for the simulation. This framework includes the identity of the revised tasks, their sequence and priority, time constraints, and crew assignments.
2. Data on the average or representative time required to perform each task or subtask, under certain standard conditions, are required as model inputs.
3. Operator workload (either overall or part by part) as a function of time is a major output.

Although the gross outline of each model conforms to the pattern implied by these three characteristics, the models differ substantially in terms of the way in which system and mission changes are reflected, and in the perturbing factors which are considered. A detailed comparison of the five models is found in the section following the model descriptions.

The following descriptions are presented in a consistent format which includes (1) a general description, (2) a listing and description of necessary inputs, (3) a listing and description of outputs, and (4) where appropriate, a tabular presentation of a typical cockpit evaluation operation.

THE SIEGEL-WOLF MODELS

Arthur Siegel, J. J. Wolf, and several associates at Applied Psychological Services have developed a group of models, some of which are directly relevant to attack aircraft operations. Their work has had a strong influence on most of the other modeling efforts described in this report.

The most complete and available description of the Siegel-Wolf work is to be found in a book published in 1969.[6] This work describes the "unitary or dual-operator simulation model" (which is directly relevant to attack aircraft) and a large-system model which is most relevant to shipboard systems. The description presented here is drawn largely from the book, with some additions from later reports and personal communication with the senior author. An earlier model, directed specifically toward discrete tasks in a space vehicle,[7] is not described in the book, but is of sufficient relevance to be described in a later section of this report, also.

The basic purpose of the "Unitary or Dual-Operator Simulation Model" (U/DOSM) is to provide information concerning the feasibility of completing anticipated missions within prescribed time limits, and some idea of the likelihood of failure and the degree of stress on the operator(s). The concept of "stress " has a central place in the operation of the model. Stress can arise from "falling behind" the required task/time sequence, from errors requiring repetition of tasks, from equipment delays or from problems with the other crew member in a dual operator situation.

As with most man/machine models, a task analysis must be performed before simulation can begin. The analysis provides a list of the input data required for each task, and an identification of necessarily sequential tasks. Average task performance times and standard deviation of times and average probability of success must also be estimated for each task/operator combination.

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[6] Arthur I. Siegel and J. Jay Wolf. Man-Machine Simulation Models. New York, Wiley-Interscience, 1969.

[7] Applied Psychological Services. "A Discontinuous Analytic Model for Simulating Apollo Vehicle Operator Actions and Information Exchange" by A.I. Siegel, J.J. Wolf and R. Ollman. Wayne, Pa., September 1962.

Operation of U/DOSM

The general simulation sequence is shown in Fig. 1, adapted from Man-Machine Simulation Models. The simulation makes use of a hierarchy of "tasks" and "subtasks." The "task" represents a substantial segment of a mission, such as making a carrier landing. "Subtasks" are more unitary acts, such as setting a rotary control, or check-reading a set of instruments. A task may include several scores of subtasks.

The actual subtask simulation begins after point "c" and ends at point "e" in the flow chart. For the case of a single operator, the steps in subtask simulation are (1) determining the degree of urgency - a function of remaining time available and the sum of the remaining subtask execution times; (2) calculating time-stress level - from the urgency condition, the nature of the task, and the characteristics of the operator; (3) if the subtask is a cyclic one (e.g., watching a PPI radar strobe), a delay until the next available cycle time is inserted; (4) subtask execution time is drawn from the input distribution and modified in accordance with stress level submodels; (5) subtask success/failure is drawn from the input success/failure data, modified by a stress function; (6) computing (from subtask performance) a level of goal aspiration which, in turn, affects the input conditions for the next subtask; and (7) recording all subtask results, if desired. When all subtasks in a given task have been run, the overall task data are recorded and another iteration begun, until the desired number of iterations is completed.

The steps in the process are shown in another format in Table 1 to provide for direct comparison with the other models described later. Some of the factors which enter only into relationships between crew members are deleted.

Inputs Required by U/DOSM

Input data required for each subtask for each operator include: subtask type (joint, equipment, decision, cyclic, or regular); essentiality (a value between 0 and 1); precedence (a point in time before which the subtask cannot occur, or a precedent task by the other operator in a 2-man crew); sequence (the identity of the next subtask, depending upon success or failure of present subtask); subtask time statistics; subtask success probability (unperturbed by stress and individual differences); time required to complete remaining subtasks (essential and non-essential); and goal aspiration level (a modifier to performance, based in part on preceding subtask performance).

Additional requirements, before simulation can begin, include four parameters (for each operator) and several initial conditions. The parameters are (1) total mission time limit, (2) operator stress threshold, (3) operator individuality factor (primarily a "speed" factor), and (4) cycle time for cyclic tasks.

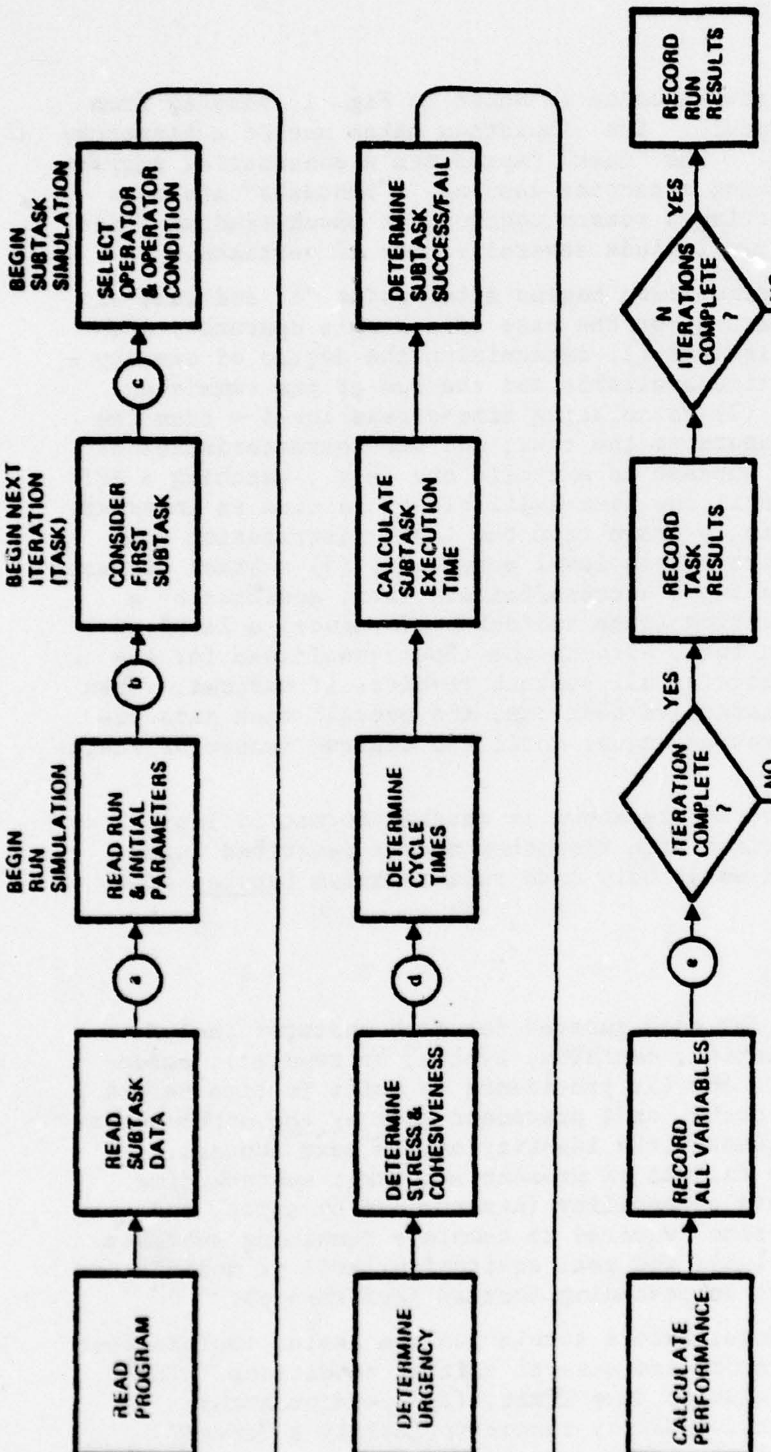

FIGURE 1. Siegel-Wolf model flow chart (adapted from Man-Machine Simulation Models).

TABLE 1. Breakdown of Cockpit Evaluation Process (Siegel-Wolf Model).

Step in Process	How Handled	
	External to Model	Internal
1. Define tasks:		
1.1 Mission description	Detailed list of tasks & subtasks, time-based.	Subtask ID, time, sequence, etc., entered into memory.
1.2 Cockpit equipment description	Not called for explicitly.	Not represented.
2. Determine basic task performance data:		
2.1 Time required/task	Reference to experimental data for mean, σ.	Stored as truncated normal distributions, by subtask.
2.2 Accuracy and/or reliability of performance	Reference to experimental data for $P_{subtask}$.	Stored as P_i; pass-fail drawn at random for a particular run, averaging out to P_i.
2.3 Sequence/priority	Assigned "essentiality:" by subtask.	Subtasks can be skipped as function of time, essentiality.
3. Modify performance per conditions:		
3.1 Reach distance & D/C placement	Reflected in 2.1, 2.2, if at all.	Not represented.
3.2 Effect of G-load, buffet, environment.	Reflected in 2.1, 2.2, if at all.	Not represented.
3.3 Effect of time stress	Reflected in time allowed for total task, and in operator "stress threshold."	Stress computed for each iteration of each subtask, based on time remaining, stress threshold, task type.

TABLE 1. (Continued.)

Step in Process	How Handled	
	External to Model	Internal
3. Modify performance (cont'd):		
3.4 Effect of individual differences	Assign values of: -Stress threshold -Individual "speed" -Initial "Goal Aspiration".	Compute current stress level (see 3.3), goal aspiration (from past performance, stress level). These values affect performance.
4. Determine Operator Task Load:		
4.1 Time stress by subtask	Affected by several inputs (see 1.1, 2.1, 2.3, 3.4).	Computed for each subtask & iteration; also average, peak, final levels.
4.2 Operator Workload	Same as 4.1.	Not computed explicitly; can deduce from data on time overruns & waiting time.
4.3 Workload by modality (e.g., hand, foot)	No relevant inputs.	No relevant output.
5. Determine System Performance:		
5.1 Probability of success	Affected by 2.2, 2.3, 3.3, 3.4 data inputs.	Computes success & failure by subtask by iteration; also summary data, by run.
5.2 Diagnostic Information	Same as 5.1.	Failures can be traced to subtasks & stress causes.

Initial conditions required included the number of iterations to be run, the initial value from which subsequent (pseudo) random numbers will be generated, and a few other identification and scaling values.

Outputs from U/DOSM

Three output options are available, in addition to the primary Final Summary Tabulation. Table 2 shows the kinds of output provided under each option.

MCDONNELL DOUGLAS CORPORATION PILOT SIMULATION MODEL (PSM)

The McDonnell Douglas PSM was developed as one part of a technique for evaluating alternative man/machine designs in terms of system performance, operator workload, and task distribution for hypothetical aircraft systems. As described in the abstract of an early McDonnell report:[8]

> "It is a stochastic, digital model with variable and parallel flow logic that allows simulation of simultaneous tasks.....The model has the following advantages .....:
>
> - Simulates the mission logic
> - Supplies visual, right hand, left hand, feet, communication, and information processing task loading.....
> - Considers simultaneous tasks
> - Provides task distributions."

In a more recent report, the PSM is described as follows:[9]

> "The model functions basically as an information store that is continually supplied with current system information.....subsequently updated...and provides probability statements concerning pilot activity as an output."

The PSM is so named because it was originally developed to simulate a pilot's workload in a tactical fighter aircraft. In the 7 years since its genesis, the model has been refined and expanded. It is now capable of simulating the workloads of multiple crews to a maximum of 100 individually identified operators.

[8] McDonnell Aircraft Co. Digital Simulation Model for Fighter Pilot Workload, by C.F. Asiala, Jr. St. Louis, MO, MAC, September 1969. (MDC Report A0058, publication UNCLASSIFIED.)

[9] Aerospace Medical Research Laboratory. Advanced Fighter Concepts Incorporating High Acceleration Cockpits, Vol. 4 - Pilot Performance Analyses, by J.M. Sinnett and C.F. Asiala. Wright Patterson Air Force Base, Ohio, AMRL, July 1973. (AMRL Report No. AMRL-TR-72-116, page 39, publication UNCLASSIFIED.)

TABLE 2. Available Outputs - Siegel-Wolf Model.

Type of Output	Output Options: Run Summary	Task Summary (Optional)	Subtask Summary (Optional)	Plotted Results (Optional)
Item ID	Run number; time duration.	Run no., iteration no.	Subtask no. & type; essentiality.	Run number.
Operator ID	Oper. no.; stress threshold; speed factor.	Same as run summary.	Operator no.	Operator no.
Descriptive Statistics	No. of iterations; no. successful; % successful; av. time per iteration; av. time overrun; av. stress; av., max., min. and final Goal Aspiration; av. waiting time. Also, for subtasks: no. failed; no. ignored; no. on which peak stress occurred; time spent on failed subtasks; etc.	Task outcome; total time used; time overrun; total waiting time; stress-peak & final; goal aspiration-max., min. and final.	Subtask outcome subtask time; waiting time; stress; cohesiveness.	Average time used; stress-peak & final; prob. of success; waiting time; subtasks ignored & failed.

The PSM has the automated capability of processing flight simulation data. Hence, early predictions can be validated by actual testing.[10]

The relationship between the PSM and other elements of the overall evaluation technique is shown in Fig. 2, adapted from a recent paper.[11]

The use of the model requires a number of sequential actions by the user. They include:

1. Preparation of scenarios
2. Description of the crew station(s), including controls and displays and their locations.
3. Preparation of Operational Sequence Diagrams (OSD's).
4. Description of each operator task in a standard format. Each task is described as an Information-Processing-Action (IPA) sequence. Provisions for skipping elements of the sequence make it possible to use the same sequence for all kinds of tasks.
5. Task execution time distributions and error probabilities for each task must be generated.
6. "Running" the model for a large number of iterations (model iteration limit is 100).
7. Reviewing and analyzing the statistical data outputs.

The same procedure can be used with different cockpits, task assignments, etc., as needed.

Inputs

Like all man/machine system models, the PSM is critically dependent upon the input data which describe the mission, the vehicle, the operator, and the operating sequences required. Among the inputs required are:

1. Descriptions of all tasks and values of associated time-related mission variables. ("Tasks" are defined as simple actions such as "scan display" or "adjust control".)
2. The distribution of expected time durations for each task element, from external sources.
3. Interactions among tasks, from operational task sequence diagrams.
4. Likelihood of error in performing each task, from external sources.

---

[10] Flight Dynamics Laboratory. Definition Study for an Advanced Fighter Digital Flight Control System, by D.S. Hocker, I.G. Pope, G.R. Smith, and G.J. Vetch, Wright Patterson Air Force Base, Ohio, FDL, June 1975. (AFFDL Report No. AFFDL-TR-75-59, publication UNCLASSIFIED.)

[11] Carl F. Asiala. "Advanced Man/Machine Evaluation Techniques" presented at the American Defense Preparedness Assoc., Avionics Section, Fall Symposium, Huntsville, Ala., 12-13 November 1975.

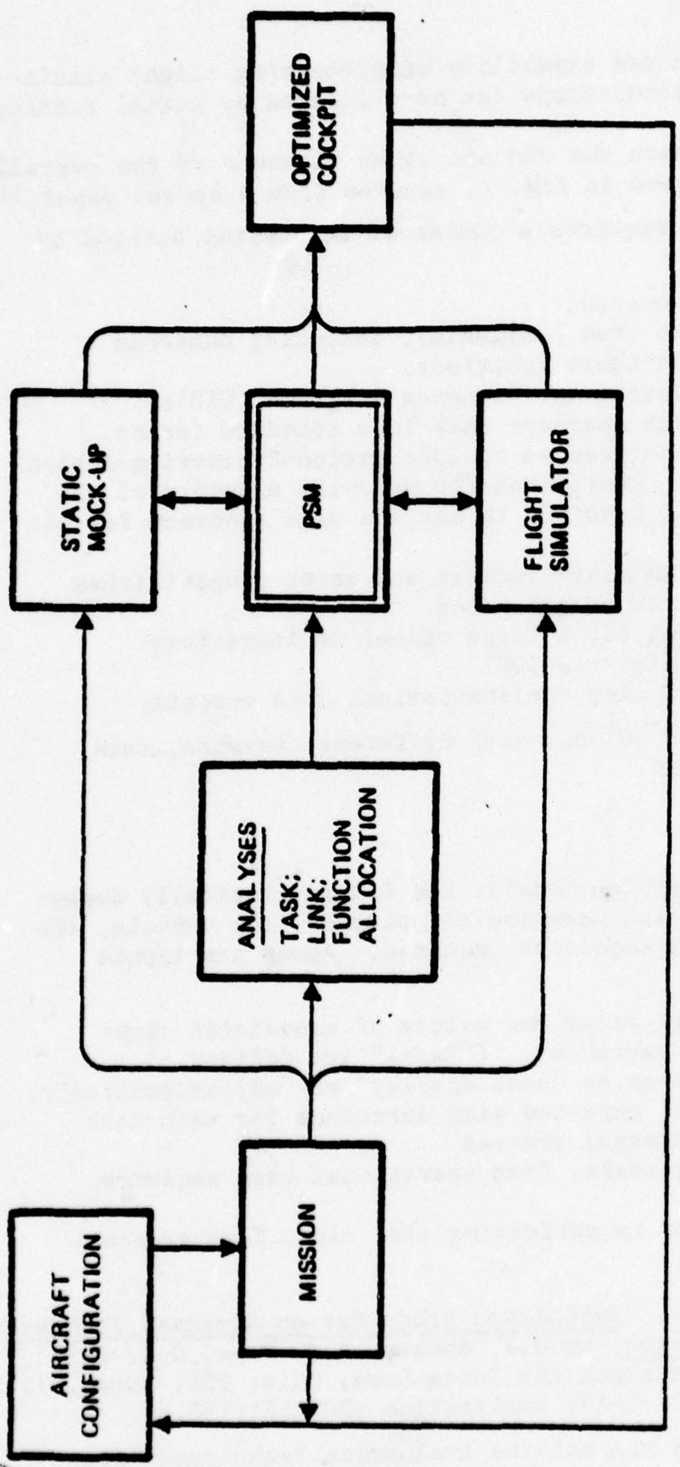

FIGURE 2. Place of Pilot Simulation Model (PSM) in McDonnell Douglas Man/Machine Evaluation Technique (adapted From "Advanced Man-Machine Evaluation Techniques," by Carl Asiala. November 1975.

5. Criticality and difficulty of each task.
6. Locations of all controls and displays.
7. Time penalties associated with task sequences between widely separated controls/displays (called "inter-zone penalties").
8. Dimensions of operator visual field, including effects of visors, etc.
9. High-G effects on operator functions, in tabular form.
10. Equipment identification and reliability.
11. Cognitive and perceptual motor skills associated with each task.

Outputs

The primary outputs of the PSM are those associated with operator workload and mission-characteristic statistics. Specifically, outputs include:

1. Pilot workload as a function of time.
2. Workload of individual pilot "channels" (e.g., "right hand," "visual").
3. Timeline plots.
4. Equipment utilization data.
5. Mission success probability.
6. G-load on pilot as a function of time.
7. Required display character size and luminance, as a function of time.

Simplified Simulation Flow

A typical cockpit evaluation process, broken down into major sub-elements, provides a way of demonstrating what parts of the evaluation are handled internal to the model, and what parts must be done externally. Such a breakdown, at a gross level, is shown in Table 3.

VOUGHT WORKLOAD SIMULATION PROGRAM (VOUGHT-WSP)

The Vought Corporation has developed and is using a cockpit workload prediction model which was initially referred to as a Work Requirement Model,[12] and now as a Workload Simulation Program.[13]

---

[12] T.J. Klein and W.B. Cassidy. "Relating Operator Capabilities to System Demands," presented at 1972 Human Factors Society Annual Meeting, Los Angeles, CA., October 17-19, 1972.

[13] Vought Systems Division, LTV Aerospace Corp. Pilot Task Analysis/Task Description Report: TA-7C Aft Cockpit vs A-7E Carrier Recovery, by T.J. Klein and A.A. Hall. Dallas, Texas, LTV, March 1975. (Report No. 2-54220/5R-17025, report UNCLASSIFIED).

TABLE 3. Breakdown of Cockpit Evaluation Process (McDonnell Model).

Step In Process	How Handled	
	External to Model	Internal
1. **Define tasks**:		
1.1 Mission description	Detailed task list; time-based.	Available time stored, by phase, as a distribution.
1.2 Cockpit equipment description	Locations of C/D elements; type of C/D elements (see 2.1 & 2.2).	Location "zone" stored for each piece of equipment.
2. **Determine basic task performance data**:		
2.1 Time required for each task	From literature or man-in-loop simulation, by D/C type.	Stored distribution, by task.
2.2 Accuracy and/or reliability of task performance.	From literature or man-in-loop simulation, by D/C type.	Stored as human probability learning curve.
2.3 Sequence and priorities	Assigned criticality during task analysis.	Criticality code attached to each stored task.
3. **Modify performance data per conditions**:		
3.1 Time adjusted for reach distance	Penalties obtained, from lit. or sim., by reach distance.	Time penalty computed, using location (from 1.2) and stored data.
3.2 Penalties for G-load		
3.2.1 Grayout penalty	G vs flight conditions; grayout threshold - from outside sources.	Compute G-load dynamically; consult stored data & delay if G>G threshold.
3.2.2 Time penalty	Time penalty vs G, by task, from outside sources.	Compute G-load dynamically; look up stored time penalty; apply penalty to basic task time.

TABLE 3. (Continued.)

Step in Process	How Handled	
	External to Model	Internal
4. <u>Determine operator task load</u>:		
4.1 Task load by task and by sensor/ effector		Select basic task time by Monte Carlo from stored data (2.1); modify by penalties (3); compare with available time (1.1) selected by Monte Carlo; compute % task load for each member.
4.2 Total operator load		Sum element loads from 4.1; print out as function of mission phase. (Note that several tasks may occur at same time; load may be >100%).
5. <u>Determine system performance</u>:		
5.1 Equipment utilization		Output frequency of use; percent utilization by mission phase.
5.2 Control/display location effects (link analysis)		Output all "look links" and "reach links" between C/D elements.
5.3 Displayed data req'ts	Stored data on visual capability under G-load and other environments.	Generate (from stored data) symbol size & luminance minimums, by phase.

TABLE 3. (Continued.)

Step in Process	How Handled	
	External to Model	Internal
5.4 Accuracy/reliability	Input human reliability by task.	Modified by input "learning curve" Output probability of success.

A brief description of the program is found in an internal document provided to the writer by J. E. Burke of the Vought Corporation:

"The workload simulation program is a time-based computerized mathematical modeling technique for predicting workload levels imposed upon the human by mission and system parameters. The model provides discrete task (switch-throwing, etc.) and continuous-control task (stick/throttle modulation) difficulty level predictions over the spectrum of mission flight segments.

"General capabilities of the model include:

- crew sizing and man-machine function balancing
- prediction of the impact on crew workload demands of variations in aircraft design parameters, control/display arrangement, avionics equipment, flight path deviation tolerances, system integration logic (moding), and mission and environmental considerations.
- identification of potential task overload points for man-machine system trade-off consideration
- assessment of the impact on crew workload demands that can be expected to result from assigned system functions
- predicting work response levels from known systems demands
- relating tracking accuracy to system workload demands
- combining tracking and procedural workload components"

General Structure

The model is composed of two primary sub-models - one for discrete control tasks, the other for continuous control. Input data flow into one or the other of the submodels. The outputs from the two submodels are merged, after separate "task load indices" have been computed, yielding a total workload by mission phase, as required by Mil-H-46855.

The overall organization of the model is shown in Fig. 3 and was adapted from the internal Vought Corporation report cited in the preceding paragraph.

Inputs

As shown in Fig. 3, inputs are broken into three types.

Mission/Task Variables. These inputs provide the characteristics of the mission (e.g., segment sequence, flight path tolerances, time envelopes) required to call up all the tasks involved in the mission. Priorities (on a five-point scale) are assigned to each task. For each cockpit task, a task duration time (TDT) estimate, based on empirical data, is input.

Cockpit Configuration Variables. These inputs include cockpit geometry and control and display locations in the cockpit. Total task times required are computed and include the TDT estimate and the additional effects of control and display locations.

Controlled System Variables. These inputs relate to aerodynamic parameters of the aircraft, and are used to compute the rate at which deviations from flight path will occur. These deviation rates, together with the flight path tolerances mentioned above, define the task loading in continuous control tasks.

Outputs

Figure 3 indicates only some of the direct outputs of the model. However, the output includes additional information which is useful in evaluating specific crew station designs. For discrete tasks, the mean task total performance time required is divided by the available time and summed on an earliest-time-of-initiation, latest-time-of-completion basis to generate "worst-case" discrete task time stress (T-S) values.

An additional output available for evaluation is "time-within-tolerance" for all three flight path channels for continuous control tasks - a measure of tracking accuracy and quality of mission performance.

The summed (discrete plus continuous task) workload level for each time segment is compared with a "workload limit" (which is empirically determined, and varies as a function of the percent mix of continuous/discrete tasks during that segment) to determine whether a potential overload exists. A second-by-second plot of workload demand is the output.

Simplified Simulation Flow

A typical cockpit evaluation sequence for a discrete task is shown in Table 4. It shows how various task, mission and operator factors are handled, either internal to the model or externally.

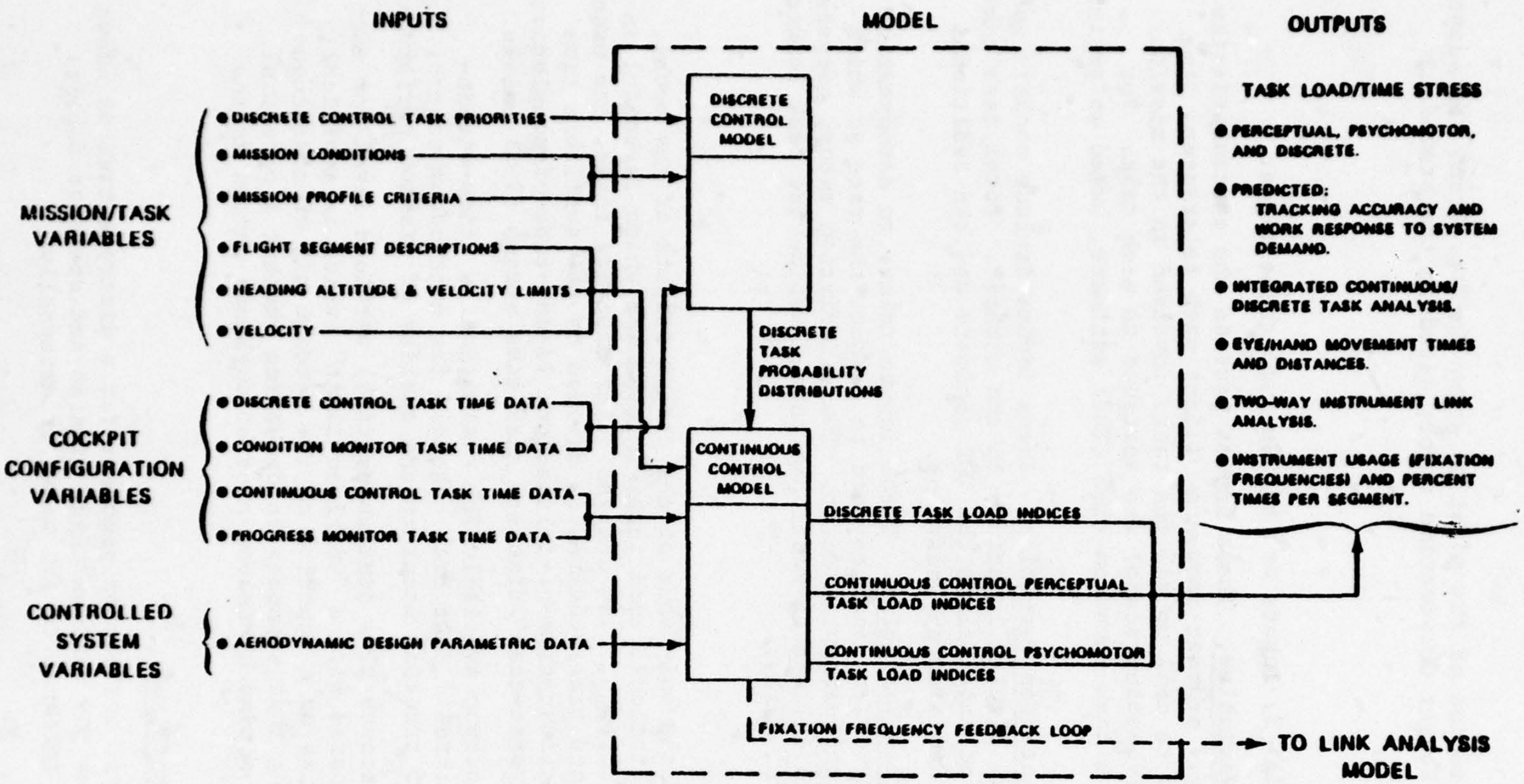

FIGURE 3. Vought Workload Model - Simplified Flow Diagram.

TABLE 4. Breakdown of Cockpit Evaluation Process (Vought Model).

Step in Process	How Handled	
	External to model	Internal
1. Define Tasks:		
1.1 Mission description	Time-based detailed task list per mission profile segment.	Store sequence & times required per task. Compute segment time envelopes.
1.2 Cockpit equip. description	Locations of C/D elements; types of C/D elements.	Store, by equipment x, y, z locations.
2. Determine discrete task performance:		
2.1 Time required to perform each task	Median value, from test data or estimates.	Stored data by task.
2.2 Time to reach or look at next task	Test data used to develop algorithms.	Algorithm for "reach time" or "look time" as function of distance.
2.3 Accuracy/reliability of task performance	Discrete-not-computed. Continuous-determine control tolerances by mission profile segment.	Discrete-not computed. Continuous-generates performance data from task description, control tolerances, and empirically generated equations.
2.4 Sequence & Priorities	Assign criticality by task & phase. Frequency of monitoring determined by error nulling frequency requirements.	Interlace tasks, using frequency & criticality, by Monte Carlo method.
3. Modify performance data per conditions		
3.1 Tasks delayed by "overload" (see 4.1)	Establish critical task load empirically. Assign priorities (see 2.4).	Delay least critical task & recompute task load.

TABLE 4. (Continued).

Step in Process	How Handled	
	External to model	Internal
3.2 Penalty for hi-G, or any other degrading environmental condition	Determine G-related decrements; tabulate.	Test for G & apply decrement if needed.
3.3 Modify for night, weather, defenses	Establish new tasks; criticalities, decrements, tolerances.	Stored data changed.
4. Determine operator task load:		
4.1 Manual "time-stress" (T-S) for discrete tasks	Available time for each task determined (see 1.1 & 2.4).	Required time (2.1 & 2.2) compared with available time, by task.
4.2 Sensory "time-stress" for discrete tasks	Same as above.	Same as above.
4.3 Combined "time-stress" (discrete plus continuous) by segment of mission profile *	Same as above.	Discrete "T-S" combined with continuous task "T-S", once per second.
4.4 System operator workload demand	Recommended "T-S" design limit determined empirically.	"T-S" computed, compared with "T-S" recommended.
5. Determine system performance:		
5.1 Accuracy/probability of success	See 2.3 and 2.4.	Computes probability of remaining in tolerance in all channels.
5.2 Control/display location effects (link analysis)	See 1.2 & 2.2.	Computes control-to-control and display-to-display link values.

*T-S for "continuous" tasks is determined by comparing the (empirical) time required to correct a deviation with the error correction rate imposed (see 2.3 and 2.4).

NAVAL AIR DEVELOPMENT CENTER HOS MODEL

The Naval Air Development Center (NADC) at Warminster, Pa., has directed two large-scale efforts in operator/cockpit modeling. One of these efforts (known as "CAFES") was performed under contract by Boeing Aircraft Corp., and is discussed separately. The other major effort (known as the Human Operator Simulator, or "HOS") has been performed by Analytics, Inc., as well as by personnel at NADC and, in earlier years, at the Naval Missile Center (NMC), Pt. Mugu, California. Commander R. J. Wherry has directed the HOS work from its inception at NMC. Funding for the program has come from the Naval Air Systems Command.

The HOS program, including the Human Operator PROCedures (HOPROC) Language, the HOPROC Assembler and Loader (HAL), and the Human Operator Data Analyzer/Collator (HODAC), is an ambitious attempt to model the human operator in all his complexity from micro-models at a detailed behavior level. A recent paper by R. J. Wherry, Jr., the originator of the HOS program, states:[14]

> "The Human Operator Simulator (HOS) digital computer program developed over the past seven years, is capable of simulating the performance of a goal-oriented, adaptive, trained human operator in a complex weapon system down to the level of hand reaches, control device manipulations, eye shifts, absorptions of visual information, and internal information processing and decision making.
>
> The combined effects of an operator's role, the displays and controls he would be given and their layout, and the various situations with which he would be confronted are obviously complex. Existing human performance prediction techniques do not handle such complex, interactive situations in which there are hundreds of variables that could effect his performance. It is axiomatic that such complex situations must be created and exercised to find out what will really happen to the operator."

The objective of this elaborate modeling effort is to provide an acceptable, valid substitute for "expert opinion" in the design and evaluation of complex systems. Again, in Wherry's words:[15]

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[14] R.J. Wherry, Jr. "The Human Operator Simulator - HOS" in Monitoring Behavior and Supervisory Control, ed. by T.B. Sheridan and G. Johannsen. NATO Conference Series, III Human Factors, Vol. 1. New York, Plenum Press, 1976. p. 283

[15] R.J. Wherry, Jr. "The Human Operator Simulator - HOS" in Monitoring Behavior and Supervisory Control, ed. by T.B. Sheridan and G. Johannsen. NATO Conference Series, III Human Factors, Vol. 1. New York, Plenum Press, 1976. p. 284.

"The need to create the situation and to collect human performance data from the created situation led to the conclusion that simulated man-in-the-loop, dynamic simulation would be an acceptable substitute if human operator behavior in a complex crew station could be simulated with sufficient accuracy and detail. With the advent of high speed, digital computers, a sufficiently sophisticated model of how a human operator behaves became feasible. HOS is an attempt at such a model."

The attainment of the HOS objective is critically dependent upon the ability of the user to construct or acquire adequate "micro-models" from which to build up the larger procedures involved in system operation. These micro-models must represent such "micro-behavior" elements as reach, grasp, twist a control, read a digit, remember a digit. If the assemblage of micro-models is to reflect accurately the effects of such variables as control knob size and spacing, training level, temperature stress, etc., then all micro-models must either (a) be accurately sensitive to those variables, or (b) represent actions which are unaffected by them.

One major difference between the HOS approach and the two preceding models is the use of more finely granulated behavior elements described above, rather than "I-P-A" units (McDonnell) or "tasks" (Vought). The HOS model also postulates a greater variety of responses to an event (e.g., "recall present setting" or "look at present setting") and more detailed record-keeping on position of body parts (e.g., HOS maintains 3 positions for each hand - "present," "preferred," and "relaxed"). The entire HOS concept envisions a much more fluid, adaptive operator model than other models in use.

General Structure

A decision must be made, before describing the structure of HOS, whether to describe the conceptual HOS or the existing, operating version. While the concept of HOS is most interesting and valuable as an outline of a sophisticated approach to operator modeling, the emphasis in this review on "available" models seems to require that the operating versions are the ones to be described here. It is recommended that the interested reader obtain the extensive documentation on HOS before embarking on any substantial effort to develop new models or model elements.[16-19]

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[16] Analytics. The Human Operator Simulator, Volume I, Introduction and Overview, by M.I. Streib. Willow Grove, PA., August 1975. (Analytics Technical Report 1117-1, publication UNCLASSIFIED.)

[17] Analytics. The Human Operator Simulator, HOS Users Guide, by M.I. Straib. Willow Grove, PA., October 1975. (Analytics Technical Report 1181-A, publication UNCLASSIFIED.)

The basic structure of the HOS system in simulating an aircraft mission would be as shown in Fig. 4, from Analytics' Introduction and Overview volume (referenced above). Unlike the other models, the simulation is driven by a procedure-based "Mission," which is a branching series of tasks or steps. The impact of the mission on the operator is through one of two types of "change" signals: (1) mission-specified changes (such as turn points) and (2) corrective changes (in response to exogenous events, or to a displayed quantity drifting outside prescribed limits).

When a change (or "ALTER" in HOS terms) is specified from the mission, the HOS model first checks whether the "new" value already exists as a result of some earlier action (see "Recall" in Figure 4). If not ("Decision"), it calls up a "change value" subroutine (using "Anatomy Mover"). If the value is already in effect, the operator "memory" (a function of learning level and elapsed time, or "O-State") is tested to determine whether the value must be interrogated or not. This alternative clearly adds to the flexibility of operator response; validity depends, of course, upon the algorithms and input quantities.

Parallel actions can occur, if they are in different "faculties" (e.g., body movement and memory recall).

Variability of performance is to be handled in HOS by time-varying "O-states" which presumably reflect accurately the effects of practice, stress, etc., rather than by Monte Carlo methods. However, in one closely-documented simulation application, it is stated that "though we hope eventually to develop a detailed theory of how display-reading performance is influenced by training, fatigue, attention and automaticity,..... the quantitative version of that theory is not to be achieved in the near future."[20] The operator can "choose" to omit steps in the procedures if they are not required by the current system status. He can also delay or omit steps when the criticalities of low priority tasks remain below other criticalities. Considerable flexibility is available in the procedures coding to dynamically change criticalities as a function of "current" events during simulation.

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[18] Analytics. The Human Operator Simulator, Volume VI, Simulation Descriptions, by M.I. Streib. Willow Grove, PA., December 1975. (Analytics Technical Report 1181-B, publication UNCLASSIFIED.)

[19] Analytics. The Human Operator Simulator, HAL Programmer's Guide, by M.I. Streib. Willow Grove, PA., March 1976. (Analytics Technical Report 1181-C, publication UNCLASSIFIED.)

[20] Analytics. Development of a Quantitative Display Reading Model for HOS, by M.I. Streib. Willow Grove, PA., May 1975. (Analytics Technical Report 1117-F, p. 4-3, publication UNCLASSIFIED.)

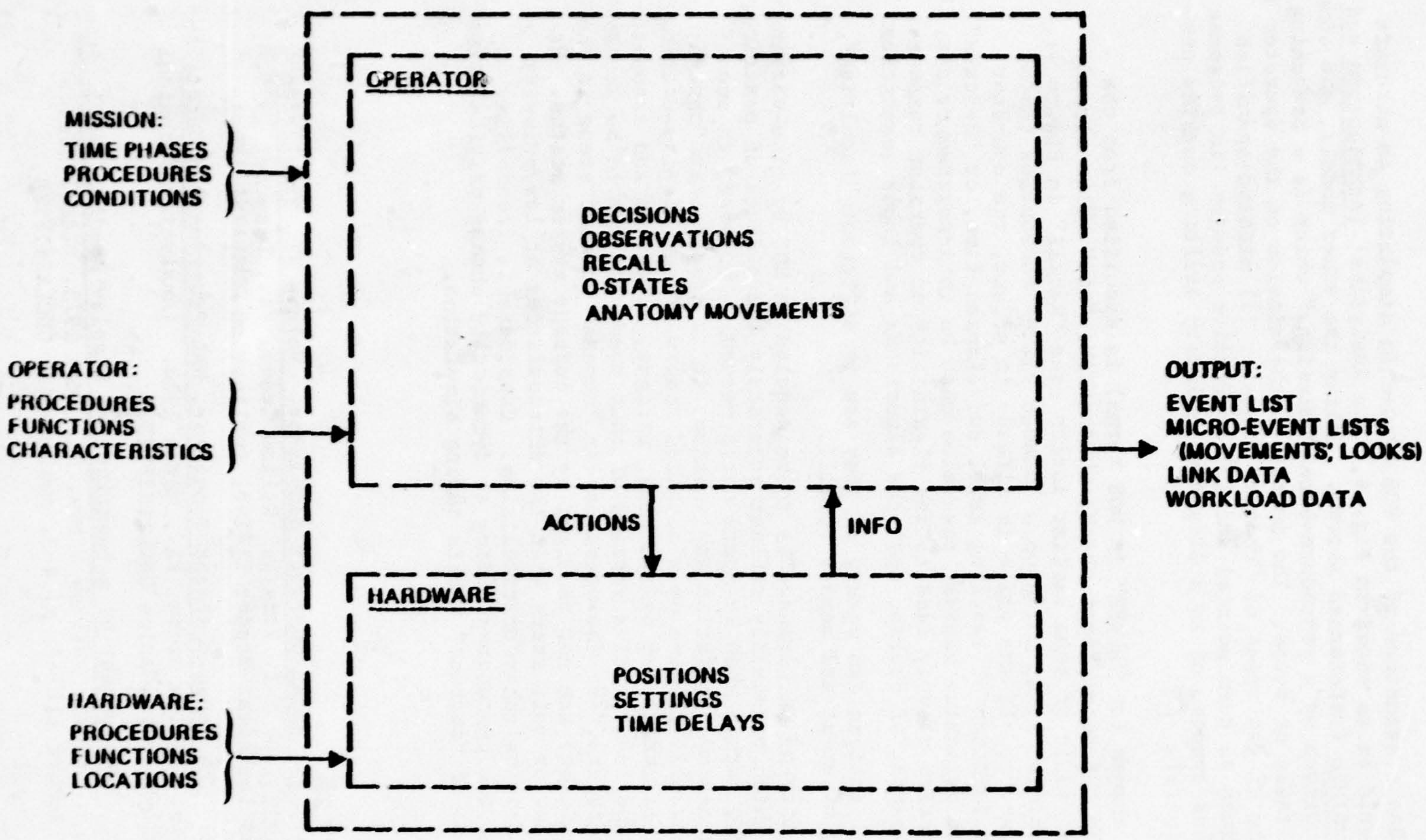

FIGURE 4. Simplified Functional Flow - HOS Model (adapted from Analytics #1117-1, 1975).

Program Modules

The HOS model itself (as distinct from the inputs, outputs, etc.) is made up of four principal modules.

1. The Decoder. This module receives instructions (from the mission-based inputs) and exercises a series of queries, to determine the status of the relevant equipment and operator elements, followed by a decision as to the best sequence of steps to be followed.

2. The Multiplexor. This module maintains priorities of possible procedures, and sequences the instructions sent to the Decoder, including interrupts if required. If no action is required, the multiplexor will either return the system to an existing procedure, or enter a "relax" mode (in which operator recovery from fatigue could be modeled, although it is not presently represented.)

3. The Estimator. This module models the sensing and memory aspects of the operator actions. For example, whenever an operator procedure calls for "reading" a device, the estimator begins a sequential process: (1) If the operator is already in "contact" with the device, he is assumed to "read" or "absorb" its value; (2) if he is not in contact, recall of the value is attempted; (3) if recall cannot be accomplished, he must move the necessary element to the equipment; and (4) then absorbs the reading. Time charges are assessed for all actions.

4. The Banker. This module accumulates time charges (as well as potentially keeping track of changes in O-state due to fatigue, etc.).

Inputs

Inputs to HOS can occur in two ways. The HOPROC procedures language is used to provide five classes of inputs, as described briefly below.[21]

1. "Title declarations." These inputs identify the controls, displays, symbols, and settings associated with the cockpit interface, and the "O-states" of the operator(s).

2. "Operator functions." These inputs are in equation form and describe the mental computations available to the

[21] Analytics. The Human Operator Simulator, Vol. I, Introduction and Overview, by M.I. Streib. Willow Grove, PA., August 1975. (Analytics Technical Report 1117-1, pp. 2-2 to 2-5, publication UNCLASSIFIED.)

operator. The equations may incorporate the values of other devices or functions.

3. "Hardware functions." These inputs are in equation form, similar to the "operator functions."

4. "Operator procedures." The user seldom accesses the basic "microactivities"; these are ordinarily called and executed by a HOPROC instruction (like ALTER). The instruction is automatically compiled, and a microactivity sequence is generated based on internal rules. All procedures, whether system-inherent or user-constructed, are treated as units for execution purposes; they function like subroutines.

5. "Hardware procedures." These are parallel in form to the "operator procedures."

In addition to the above HOPROC-moderated inputs, the HOS receives several types of direct inputs:

1. Initial states of devices and functions, and initial "O-states."

2. Locations of all devices.

3. Initial "hab" strength (a measure of how well an operator function has been learned, and how long since it was reinforced).

4. The amount of time required for a simple interrogation of a display.

5. The accuracy associated with an estimate of expected value of a display or control setting.

6. Indicators associated with equipment, specifying the type of equipment, and such parameters as the time required to make an adjustment.

Outputs

The outputs available from HOS are printouts of all instruction executions and event times. The compilation of this raw output material into useful quantities (such as loading, number of events by class, timelines, etc.) is performed by a separate module called HODAC (Human Operator Data Analyzer/Collator). HODAC can generate seven types of reports:

1. Timeline Analysis - a listing of activities, by body part, on a time base.

2. Device-by-Body Part - cumulative statistics on the amount of time spent by each body part, in each type of activity, on each device.

3. **Device-by-Usage - cumulative statistics on number of actions and time spent in each type of action.**
4. **Device-by-Procedure - same as above, but keyed to task elements (e.g., "remove the symbol").**
5. **Procedural Analysis - cumulative statistics as above, but keyed to significant procedure types (e.g., "deciding").**
6. **HODAC Label Analysis - cumulative statistics on the occurrences of HODAC "statement labels" by mission procedures.**
7. **Link Analysis - cumulative statistics on movements by body part, from device to device in the cockpit.**

Typical Cockpit Evaluation

The HOS model, in its present (1976) state, is not sufficiently complete to permit a whole mission cockpit/workload evaluation process which is directly comparable to the preceding models. Table 5 presents those elements available from the documentation, in as nearly comparable form as feasible. It should be kept in mind, however, that the HOS model has not been exercised in a whole-mission, whole cockpit simulation as have the preceding models. The most extensive documented airborne mission simulations are two segments of the Air Tactical Officer duties in the LAMPS helicopter system.[22] The two mission elements are:

1. Keyset entry and retrieval. This task involves a keyboard and an alphanumeric display. The simulation involves modification of settings in a stores-control system.
2. Fly-to Contact. This task involves a cursor control stick and two associated switches, and a map-type display which shows contact locations and the location of the cursor. The simulation involves erasing three existing contacts on the display.

BOEING "COMPUTER AIDED FUNCTION-ALLOCATION SYSTEM" (CAFES)

CAFES is, as the name implies, a <u>system</u> for computer-aided cockpit analysis and design. It is made up of several modules, some of which are "models" in the sense that we have used the term before. Taken collectively, CAFES is intended to include essentially all the features

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[22] Analytics. The Human Operator Simulator, Volume VI, Simulation Descriptions, by M.I. Streib. Willow Grove, PA., December 1975. (Analytics Technical Report 1181-B, publication UNCLASSIFIED).

TABLE 5. Elements of Cockpit Evaluation Process (HOS Model).

Step in Process	How Handled	
	External to Model	Internal
1. Define tasks:		
1.1 Mission description	Event-based, branching, detailed task list.	Stored in "Mission"; fed to "Decoder".
1.2 Cockpit equipment	Locations of all equipment.	Stored.
2. Determine task performance:		
2.1 Time required to perform task elements, or to transition from task-to-task	Handled both externally and internally. Most time elements are determined by internal algorithms while other estimates are input parameters to provide for variability.	
2.2 Accuracy/reliability of operator action	Required accuracy is input; system will manipulate absorptions and control the inputs to try to achieve this accuracy level.	Sequence can be changed by the operator or dynamically by the procedure, according to the criticality value.
2.3 Accuracy/reliability of operator memory	Establish memory functions in terms of practice, elapsed time, 0-state, etc.	Operator memory of display/control states is fallible, and is time-variable.
2.4 Sequence and priorities	Criticality assigned to tasks.	Criticality modified as function of mission state, displayed value, and time since last reading. Sequence varies with criticality, and criticality can vary with sequence.

TABLE 5. (Continued.)

Step in Process	How handled	
	External to Model	Internal
3. Modify performance per conditions:		
3.1 Effects of stress, fatigue, etc.	Establish "O-state" theory* and functions.	Algorithms planned.*
3.2 Effects of weather,, defenses, etc.	Defined by "Mission" inputs.	No change in operation.
3.3 Effects of posture, anthropometrics	Anthropometry input to ANATOMY MOVEMENT model.	Keeps track of limb positions; computes times for required moves.
4. Determine Operator Task Load		
4.1 Overall activity level		Output "Timeline Analysis" report.
4.2 Load by body element		Output "Device-by-Body Part" report.
4.3 Body movement load		Output "Link Analysis" report.
4.4 Effects of overload		"Overload" not permitted; unneeded tasks may be delayed/omitted.
5. Determine System Performance:		
5.1 Effects of cockpit arrangement	Select alternative arrangements.	Output "Link Analysis" report.

*Performance algorithms, internal to model, are planned but not available. External factors are managed by defining alternative procedures for the operator to shift to when his performance degrades or improves.

used in any of the models previously described. However, not all modules are completed and documented at this writing.

Completed modules which have characteristics similar to the other models described in this report are the Function Allocation Model (FAM), which is made up of two, almost independent sections, and the Workload Assessment Model (WAM). The Computer Aided Design (CAD) module is entirely geometrical, but is not a man/machine model. Reach envelopes for CAD have to be generated by the user and are a required input for the CAD Reach Analysis Module. CAD also has software modules which perform a vision analysis and escape interference analysis. The entire CAFES system (except HOS) is being developed by Boeing Aircraft Co., under contract to the Naval Air Development Center. The following descriptions are adapted from a Boeing report.[23]

FAM-1 (Mission Evaluation)

The Mission Evaluator Module is directed toward the limited objective of computing a mission success probability for each of a number of alternative task allocations, providing a rank-ordering of the alternatives on this single criterion. It also computes success probabilities for specific mission objectives within the mission.

Inputs. The input data required by the Mission Evaluator includes (1) a mission scenario with task list, and times for occurrence of tasks, (2) a set of mission objectives (e.g., target acquisition, threat suppression) with alternate task sequences leading to each, (3) complete operator data for each task (e.g., average time required, error rate, and a task-load rating), and (4) trial allocations of tasks to crew members and/or automated equipment. The task-load rating combines ratings of precision, concentration, reliability, continuity (non-interruptability), and priority/criticality, in simple, additive fashion.

Process and output. The objective of the process is to arrive at an overall "mission success" value which is sensitive to task allocation. The basic data for the "operator reliability" element is a "reliability-vs task execution time" function. A multi-step procedure (much of it external to the model) for arriving at operator reliability as a function of task loading is described in the Boeing report. "Task reliability" includes both the operator estimate and an input value for equipment reliability.

Overall "mission success" estimates are derived in several forms. Most simply, overall mission success is computed as the product of the task reliabilities. A "modified mission success" figure uses weights,

[23] Boeing Aircraft Co. Computer-Aided Function - Allocation Evaluation System - Volume 2, by A.F. Anderson, K.S. Renshaw, and D.C. Whitmore. Seattle, Washington, BAC, December 1974.

related to importance of the tasks, to modify the "task reliability" estimates. Separate probabilities for individual mission objectives can also be provided.

FAM-2 (Procedure Generator)

The Procedure Generator module generates operational procedures (task sequences) and computes preliminary workload statistics.

Inputs. In addition to the FAM-1 inputs, the Procedure Generator requires a set of rules and constraints for task precedence. These include mandatory tasks, prerequisite tasks, interruptability, earliest/latest start times. An important added factor is the "RNO Function" (Remaining Number of Opportunities) which has the effect of increasing the priority of a delayed task as the "latest start time" draws near.

Process and Output. The basic process of the Procedure Generator is the selection of tasks in a sequence determined by the rules and constraints (see Inputs) interacting with the dynamic RNO Function. The primary output is the operational procedure, giving task sequence and times. In addition, statistical data on top-level workload estimates (e.g., percent of time each operator is occupied) are output, for each trial function allocation.

WAM Module (Workload Assessment Model)

The basic purpose of the WAM (and the "Statistical WAM," or SWAM) is to provide more detailed workload data (e.g., for hands, eyes) as a function of system design and task allocation alternatives.

Inputs. The basic input to WAM is a highly detailed task/timeline. The kind of data required for FAM is used as a basis for the input, but much more detail is required. The mission is broken into variable time segments from one second up and crew activity by "channel" (e.g., eyes, hand) for each segment. This is all prepared external to the WAM; through the OMS, some FAM output is directly usable as WAM input.

Process and Output. The WAM converts the input data into percent workload, by channel, by segment. These workload data are treated statistically, with the results put out as tabulations and/or plots, by mission phase. Overload conditions are flagged, and detailed contributions to overload identified. A limited task shifting capability is currently included in the WAM software.

Typical Cockpit Evaluation

It should be recalled that CAFES is not a model, but a framework for a set of models, not all of which are currently functioning. It is not feasible to produce a set of iterations of a mission with a single computer run, as might be done with the first three models discussed. The separate submodels (e.g., FAM-1 and -2, WAM, CAD) are run separately, with some off-line manipulation of data between runs.

Consequently, the entries in Table 6 are not strictly comparable with those in Tables 1, 3 and 4, but represent a composite of the capabilities of the three indicated submodels.

SIEGEL-WOLF INFORMATION THEORETIC MODEL

A. I. Siegel, J. J. Wolf and R. Ollman published a report in 1962 which laid much of the groundwork for the subsequent modeling work at Applied Psychological Services as well as providing a starting point for other man/machine modeling efforts.[24] While subsequent versions of the Siegel-Wolf model have been described above, the 1962 version included significant elements which do not appear in later versions.

Specifically, the 1962 model incorporated a submodel for calculating operator action times from extensions of information theory. Contemporary experimental psychologists (notably Crossman, Fitts, Hick and Hyman) had used the "information content" of stimulus and response elements as a basis for predicting stimulus-response times in laboratory experiments. Siegel and co-workers generalized from this work, and produced two submodels - one for "execution time" of a control/display subtask, the other for communication subtasks.

All the models reviewed earlier in this report have replaced these submodels for task execution time with "input data" from unspecified sources. When directly relevant data are available for a task being analyzed, it is probably preferable to use the data rather than a model. However, the application of modeling to advanced cockpits with unconventional displays and controls is difficult because of the usual lack of directly relevant operator time data. For such cases, the use of the information-theoretic submodels might be the best available option. Limited validation results reported by Siegel in the referenced document, plus a small amount of unpublished validation data collected at Autonetics, lend considerable credibility to these submodels.

The interested reader is urged to consult the referenced report for a description of the data sources used and the formulations derived from those data.

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[24] Applied Psychological Services. A Discontinuous Analytic Model for Simulating Apollo Vehicle Operator Actions and Information Exchange by A.I. Siegel, J.J. Wolf and R. Ollman. Wayne, PA. September 1962 (publication UNCLASSIFIED.)

TABLE 6. Elements of Cockpit Evaluation Process (CAFES).

Step in Process	How Handled		
	External to Model	Mod.	Internal
1. <u>Define Tasks</u>:			
1.1 Mission description	Prepare scenario; task list, objectives.	FAM-1	Used to generate success probability.
	Same plus rules for precedence.	FAM-2	Uses to generate operational procedures.
	Same plus time phasing.	WAM	See 4.
1.2 Cockpit equipment description	Not required for FAM or WAM.		
2. <u>Determine task performance</u>:			
2.1 Time required to perform tasks	Input average per task.	FAM & WAM	Stored for use in workload and operational procedures.
2.2 Accuracy/reliability of operator action	Input error data; reliability vs task loading data.	FAM-1	Combined (with time) to give mission success probability.
2.3 Task sequences & priorities	Input precedence rules; input "priority vs time remaining" function.	FAM-2	Used to generate operational procedures.
3. <u>Modify performance per conditions</u>:			
3.1 Effects of operator variables	Included in input performance data, if at all.		
3.2 Effects of environment	Same as above.		
4. <u>Determine Operator Task Load</u>:			
4.1 Overall workload	Input operator task load data.	WAM & FAM-2	Provides workload by mission phase.

TABLE 6. (Continued.)

Step in Process	How Handled		
	External to Model	Mod.	Internal
4.2 Workload by body element or "channel"	Input "activity by channel" for mission, on time base.	WAM	Provides percent workload by channel by segment.
4.3 Effects of overload	Input operator task.	WAM	Overloads flagged & sources indicated.
		FAM-2	Sequences altered if overload occurs.
5. <u>Determine System Performance</u>			
5.1 Effects of cockpit arrangement	Input data on *operator time*/accuracy must reflect arrangement.	FAM-1	Computes "*mission success*" overall and by segment.

BASIS FOR COMPARISON OF MODELS

The purpose of the description and comparison of existing crew/cockpit models is to provide, in a single report, enough information to give potential users or modelers a qualitative picture of the available models and their areas of applicability. It is expected that anyone seriously considering the use of a model, or contemplating the construction of a new or improved one, will consult the source documentation.

MODEL CHARACTERISTICS

Computer models of systems can be classified and compared on the basis of a number of characteristics, some broadly fundamental and others more specific to the crew/cockpit system. The characteristics considered here are drawn primarily from recent treatments by Fishman[25] and by Siegel and Wolf.[26]

Deterministic vs Stochastic

A deterministic model permits the calculation of a specific, quantitative solution to a set of input conditions. Stochastic models provide statistical descriptions of a set of outputs (such as the mean and variance), but provide no basis for computing the value of a particular output for a set of inputs.

Few crew characteristics lend themselves well to deterministic modeling. This limitation leads to models which may have cascaded stochastic elements. An exception is the HOS model; although not completely deterministic, it is assumed that the variability in certain operator characteristics is insignificant for total variability in task performance. Reach, grasp, and scan can be adequately modeled by deterministic approaches, whereas cognitive functions are more likely to require stochastic modeling.

Siegel-Wolf-U/DOSM. This model is largely stochastic. Input data include distribution of times and likelihood of error, by task, sampled in multiple runs. Output includes performance statistics.

McDonnell Douglas-PSM. This model is also mainly stochastic. Input data includes distribution of times and likelihood of error, by task, sampled in multiple runs. Output includes mean and standard deviation of task times by task.

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[25] G.S. Fishman. Concepts and Methods in Discrete Event Digital Simulation. New York, Wiley, 1973.

[26] A.E. Siegel and J.J. Wolf. Man-Machine Simulation Models. New York, Wiley, 1969.

Vought-WRM. This model is largely deterministic. Task times are input as single values. Time stress is computed, once per second, as a single value. Discrete task time stress is calculated on a potential worst-case basis using earliest-time-of-initiation, latest-time-of-completion subroutine to eliminate sequence problems.

NADC-HOS - This model is also largely deterministic. Except for elemental absorption and calculation times, no task times are inputs to HOS. Times are determined by the model from the microchange times. The model for short-term recall ("hab") is explicitly stochastic. Outputs are simply times, accuracies, sequences to perform and times spent at each activity or procedure.

Boeing-CAFES - The Workload Assessment Model (WAM) of the CAFES series is a mixed model. Times for tasks are put in as nominal values, sequenced according to scenario. Task load is sampled at selected intervals; output as mean and sigma of workload.

General vs Specific

Generality in a model is achieved when a new situation can be modeled without substantial changes to the model structure. Most crew/cockpit models are rather general because they are driven by a scenario and task list, both quite flexible, and because the quantitative relationships are usually presented as tabular data from field or simulator tests. As new conditions are specified, new data sources are used as inputs. Generality typically increases further as the model becomes more microscopic, if it can be assumed that any action can be represented as a sequence of simple reflex-arc elements.

Siegel-Wolf-U/DOSM. This model is quite general in structure. New conditions are accommodated by entering new data on operator, mission, equipment and performance. Algorithms for stress, goal aspiration, etc. are unchanged.

McDonnell Douglas-PSM. This model is quite general, but new input data are required for any system change. Only a few items (e.g., G-penalties, reach distance effects) are assumed to apply to new cases.

Vought-WRM. This model is also quite general, but requires new input data for any system change. Only a few items (e.g., reach time vs distance) are assumed to apply unchanged to new cases.

NADC-HOS. Quite general, for cases which can be presumed to be made up of the same "units" (e.g., look at, grasp), with the same modifiers (e.g., O-status, "hab" strength).

Boeing-CAFES. FAM-1 and WAM are quite general, because these model elements are basically computer-based aids to the manual "task analysis" and related processes.

Holistic vs Atomistic

Man/machine interaction events can be described (hence modeled) either as a series of micro-events (e.g., "fixate," "reach," "grasp") or as smooth, integrated acts (e.g., "adjust frequency").

Siegel-Wolf-U/DOSM. This model is moderately atomistic. The subtask elements which make up the model include such actions as setting a rotary control or check-reading a set of instruments.

McDonnell Douglas-PSM. This model is also moderately atomistic. All tasks (e.g., "adjust throttle") are further broken down into Information-Processing-Action sequences.

Vought-WRM. This model is more holistic than most. Data are stored and processed at the "task" level (e.g., "observe HUD airspeed," "move throttle to ½ Mil").

NADC-HOS. The basic elements are atomistic (e.g., "reach," "grasp"). Combined units which are often repeated are also used, however.

Boeing - CAFES. This model, like the WRM, stores and processes data at the "task" level (e.g., "scan for threats," "change heading").

Analytical vs Numerical

An analytical model is one which can be expressed in algorithms or closed analytical form, permitting precise calculation of outputs from known input quantities. Numerical models represent relationships among quantities as look-up tables or other non-closed formats. Most aspects of operator performance are difficult to represent by simple analytic forms, and are represented by tables. In the following comparisons, only those items which are represented by algorithms are called out. Other relationships are handled by tables.

Siegel-Wolf-U/DOSM. "Time stress," "Goal Aspiration," and "Cohesiveness" (for a two-man crew) are computed by algorithm.

McDonnell Douglas-PSM. Performance decrements (from time-penalties to blackout) are computed as functions of G-loads. Also, time penalties for reach distance are computed.

Vought-WRM. Reach-time and look-time are computed, as a function of instrument location. Total workload is computed from continuous task and discrete task loads by an algorithm.

NADC-HOS. Reach, grasp, and manipulation times are computed by an "anatomy mover" module. Operator memory is modeled explicitly, and used to determine whether a display can be "remembered." Criticality of tasks is computed as a function of mission state and structured as an algorithm.

Boeing-CAFES. In the FAM-1 module, operator reliability is computed as a function of task load and other variables.

Continuous vs Discrete-Event

A continuous model is one in which system conditions are best represented as time-varying quantities which can have any value, within specified limits. In discrete-event models, the system condition is best described as one of a number of states.

Crew/cockpit models generally contain some elements which lend themselves easily to continuous modeling, but also include large numbers of discrete-state elements. The blending of these elements is one source of variation in treatment among the models reviewed here. The handling of continuous tasks as such is not, however, a topic of the present study.

In all the models described here, continuous tasks are blended into discrete activities by viewing them as a sequence of check-readings and corrective actions, in one form or another. The most explicit statement, and the method for blending the two, appears to be found in the Vought model.

Parallel vs Serial Operation

The operator in a complex aircraft system performs many separate tasks, using different limbs or sense organs. Some of these tasks overlap in time. The representation of these overlapping tasks requires a decision as to whether the operator can be represented as performing two acts simultaneously or not, and a method of determining task loading in the multi-task cases.

Siegel-Wolf-U/DOSM. Tasks for an individual operator are modeled serially.

McDonnell Douglas-PSM. This model permits simultaneous tasks if they use a different sensor or effector. Task load may go >100%; then, based on task priority, automatically task reordering begins.

Vought-WRM. This model also permits simultaneous tasks up to an empirically determined workload limit which is based on the discrete-continuous task mix ratio. For example, the short-term limit for a task situation consisting of discrete tasks only is 230% at the nominal long-term work capability. Lower values are established for other ratios. Beyond these levels the model delays least critical tasks to keep within the workload limit.

NADC-HOS. This model permits simultaneous actions if in different "faculties." Tasks can be delayed, omitted, or reprioritized as a function of criticality.

Boeing-CAFES. The WAM module of CAFES permits simultaneous tasks, flags overloads, and can use automatic task shifting if wanted.

Prioritizing and Queueing

In most cases of interest, tasks will arise more rapidly than they can be performed during certain critical mission phases. The queueing of unperformed tasks can be strictly first-come, first-served, or tasks can be prioritized and can even interrupt ongoing tasks, with the concomitant requirement for classification/decision rules.

Siegel-Wolf-U/DOSM. Each subtask is given an "essentiality" rating, and may have associated with it certain precedent and subsequent conditions. Low-essentiality tasks can be omitted if time stress is too high.

McDonnell Douglas-PSM. "Criticality" of each task is an input (integer 1-4). Each task input also includes a list of tasks which it will interrupt.

Vought-WRM. A level of "priority" is assigned to each task (as an integer 1-5); "frequency" of each task varies with mission segment. Sequence is set using Monte Carlo techniques, based on "criticality" and "frequency" of each task. Error nulling tasks take priority over discrete tasks.

NADC-HOS. "Criticality" of each control/display varies with mission phase and time since last checked. Sequence of acts depends upon the initial state of the device as well as operator state and mission phase. Criticality can be changed by procedures during modeling based on events or quantities available to the model.

Boeing-CAFES. FAM-2. Each task carries a "priority" (3 levels) and an "interruptability" (3 levels) rating. A set of rules (e.g., prerequisite tasks, mandatory tasks, time since latest check) determines sequence for operational procedures.

Handling of Performance Variability

Variability in performance of a repeated task is characteristic of humans. The modeling of this variability can be on a mechanistic, random basis, or an attempt can be made to model variability, wholly or in part, in terms of causes (e.g., fatigue, stress, training, attention). This characteristic is a restatement and particularization of the "Deterministic vs Stochastic" descriptor discussed earlier in this section.

Siegel-Wolf-U/DOSM. This model makes a considerable effort to accommodate performance variability both between and within operators. Individual operators are characterized by a "stress threshold," an individual "speed" parameter, and an initial level of "goal aspiration." Variability within an operator during the mission is handled in part by algorithm (e.g., stress level, goal aspiration level) and in part by random draws from performance distributions.

McDonnell Douglas-PSM. Variability due to certain environmental effects (e.g., G-load, long reach) are handled as explicit effects. Task time variability due to other causes is determined by Monte Carlo methods, from stored distributions. Output statistics are based on multiple (with a limit of 100) replications of a model run.

Vought-WRM. Variability due to some effects (G-load, visibility, reach distance) is handled explicitly. Random variability is modeled only in the distribution of tasks within time "windows." Task performance time itself is assumed to be fixed.

NADC-HOS. In theory, all variability is to be computed from "O-state" habit strength, environment, initial state of displays/controls, etc. In practice, submodels for some of these effects have not been developed.

Boeing-CAFES. Variability from run to run is not represented, except as system or rule structure is changed.

Handling of Decisions

A crew member who is monitoring the status of one or more system indicators must have available in some form a set of limits or other criteria for deciding when the indicated system status requires action. Various kinds of internal models and decision functions have been postulated in modeling the human monitor.

Siegel-Wolf-U/DOSM. "Decisions" are represented explicitly only in the "decision" task type, which is a means of providing branching in the analysis. However, "decisions" about urgency, skipping nonessential tasks, "trying harder" (goal aspiration) are represented by associated algorithms.

McDonnell Douglas-PSM. "Decisions" relative to task sequence are described under "prioritizing," above. The information processing element of each task addresses which decision logic will be used.

Vought-WRM. "Decisions" relative to task sequence are based upon priority rules plus Monte Carlo techniques. Frequency of check readings also varies as critical time nears.

NADC-HOS. "Decisions" related to choice of task (e.g., remember current setting vs make a check-reading), as well as task sequence, are based upon decision rules which are modeled explicitly.

Boeing-CAFES. FAM-2. Decisions relative to task sequence are based upon priority (see above) plus a "Remaining Number of Opportunities" factor which "forces" decisions as critical time nears.

MODELING SPECIFIC COCKPIT-RELATED EFFECTS

The Contract Statement of Work specifies several features to be evaluated explicitly: (1) monitoring, (2) interactive control performance with integrated displays, and (3) color coding. These three specific factors are discussed below.

In this discussion, the term "monitoring" is interpreted as synonymous with "check-reading." A display is checked periodically to see whether it is in a satisfactory range, or requires some corrective action.

The far more complex process of monitoring the state of the system or of the ongoing mission is discussed under the broader heading of "Integrated, Interactive Controls/Displays."

Handling of Simple Monitoring Functions

The increasing automation in avionics equipment has given rise to an increase in crew tasks which involve monitoring an automatic process. This development and some of its implications were discussed in the introduction to this report. Here the five models studied are compared in terms of their handling of simple monitoring tasks.

Siegel-Wolf Model. Monitoring or check-reading tasks are modeled explicitly in the Siegel-Wolf U/DOSM model. The frequency of check-reading actions is affected by the input "essentiality" of the task, and by precedence rules. Check-reading actions which depend upon an equipment cycle (e.g., monitoring a PPI radar display) are assessed with appropriate time delays.

McDonnell Douglas-PSM. Although all tasks are defined as I-P-A cycles (information/processing/action), provision is made for skipping the "action" portion if no operator action is required. Other than this adjustment, check-reading or monitoring tasks are handled like any others, in terms of variability of performance and the effects of mission conditions.

Vought-WRM. Check reading or monitoring is modeled explicitly as a part of the continuous control portion of the model. Frequency of monitoring is varied as a function of task criticality, control tolerances, and stability of the controlled element.

Other non-continuous monitoring tasks (e.g., checking communication channel selection) are handled as any other discrete tasks.

NADC-HOS. The HOS model literature makes explicit reference to check-reading tasks, and provides a discussion of many of the relevant variables. However, as of May, 1975, the status of the check-reading module is stated thus (in "Development of a Quantitative Display Reading for HOS," Analytics TR 1117-F, by M.I. Streib, p.4-2):

> "We intend eventually to develop a separate model for performance of check-reading tasks."

Boeing-CAFES. Both FAM and WAM modules require detailed descriptions of all tasks including ratings of interruptability, criticality, concentration, etc., as well as performance data. Monitoring or check-reading tasks would have to be handled in the same way as any other tasks, with the attendant requirement for estimation of all task descriptors for such tasks.

Handling of Integrated, Interactive Controls/Displays

The term "interactive" has not been tightly defined in the literature, but has come to be used in several different ways. Three possible levels of "interactiveness" follow.

Feedback from Operator Actions. Probably the simplest level of "interaction" without integration is one in which the control/display system provides feedback to the operator when he actuates a control. However, this level of interaction is practically universal in military aircraft, since it is a requirement of Mil Std 1472.

Change of System Configuration. This level of "interaction" is achieved when a control action results in a reconfiguration of some part of the system. For example, selection of a weapon delivery mode may result in a reconfiguration of the display on a HUD. The system has performed internal reorganization in anticipation of particular operating requirements. The result is a certain amount of integration as well, since multiple functions are tied together in a single piece of equipment.

Tutorial Display. The most sophisticated type of integrated interactive system is one which guides the operator through a series of steps initiated by the selection of an operating mode. One example is the reconfigurable keyboard, in which the legends change depending upon the preceding entry, presenting only those choices which are appropriate at the moment. Another example is a schematic or diagrammatic display, in which system configuration is presented in such a way as to highlight "next step" options after each control action.

Implications for Modeling. The characteristics which set "integrated interactive" display/control elements apart from others are somewhat elusive. However, among the properties which might serve to distinguish them are:

1. Control/display functions cannot be related uniquely to locations in the cockpit, or conversely, multiple functions will have to be associated with a given location.

2. "Display reading" as a task or subtask may have to be modeled differently when the display is reconfigurable. Content becomes all-important.

3. Multi-path task sequences will have to be provided in the model. This is not a new requirement since even the simplest, hard-wired avionics system will permit alternative scenarios, but the branching will be more pervasive.

Examples of Integrated, Interactive System Tasks. In all the cockpit/operator models described in this report, a detailed list of tasks and task options is required to "drive" the model. The difference between dedicated display/control equipment and integrated, interactive systems will be reflected in the nature of the tasks.

A brief task sequence is presented in Table 7 for an A7-E aircraft with conventional avionics, and with an integrated, interactive control/display set. It will be noted that, for this sequence, the nature of the tasks changes substantially, indicating that new sources of time and accuracy data will be required when modeling the newer systems. However, it doesn't appear that any difference in model structure would be required for this type of integration.

A higher level of system autonomy is planned in certain future avionics systems, and would seem to require a different level of description and analysis. An example might be an "automated" ECM/ECCM system. Here the equipment would be expected to sense the electronic environment and to make appropriate responses, based upon a set of decision criteria. The crew might normally receive only status information, such as threats detected, direction of each, countermeasure being used, and remaining capacity (such as chaff, number of jammers, decoys).

Here the crew member is expected to monitor the tactical situation, and to intervene only when he feels intervention is required. To describe this relationship as a series of tasks, with associated performance times and error rates, does not appear on the surface to be feasible.

Adaptability of Present Models - The models reviewed here vary somewhat in the extent to which they are adaptable to sophisticated interactive designs. The quality and depth of the task-analytic work required for model inputs will also affect the handling of these sophisticated systems.

1. Siegel-Wolf Model. Interaction at the simple level (i.e., system responds to operator input; operator perceives resulting system change; operator selects next action in part as a function of perceived system response) is handled in early versions of the model by a "decision task" and a Monte Carlo choice from the options available at the decision. A later version (1971) adds the option of stopping the simulation at a "decision" point, letting the user make the decision, then starting again. This version in effect "models" the decision process by using a surrogate crew member. Presumably a "tutorial" interactive system would be simulated in this way. However, as the system becomes more autonomous, the "surrogate crew member" might become essential throughout the simulation.

The effects of "integrated displays" (i.e., multi-purpose, reconfigurable) are not modeled explicitly, but would have to be reflected in the input data.

TABLE 7. Weapon Selection - A7-E Snakeye.

Action	Tasks: Conventional	Tasks: Integrated/Interactive
1. Select Stations	1.1 Look at "STATION SELECTOR" displays. 1.2 Select desired station(s). 1.3 Actuate.	1.1 Press "STRS MGMT" key. 1.2 Look at illuminated option keys. 1.3 Press "STR" key. ("MK 82-SI" appears on key.) 1.4 Press "MK 82-SI" key. (MK 82-SI 1 appears on Stores Mgmt display). 1.5 Press "STA" key. (5 station designation keys appear.) 1.6 Press desired station(s).
2. Select Delivery Option	(Note: All delivery options pre-set in wpn. bay.) 2.1 Look at stores mgmt panels. 2.2 Select "TAIL FUZE" (green light appears). 2.3 Check selections visually on individual panels.	2.1 Press "OPT" key (Delivery option keys appear). 2.2 Press desired delivery option keys (e.g., ripple interval, fusing option). 2.3 Check selections on tabular display.

"Interaction" of crew members with mission conditions is represented dynamically in this model by the varying values of "time stress" and "goal aspiration."

2. McDonnell Douglas PSM. Interaction between system/mission status and performance is provided in each task by (1) a variable time delay, to allow waiting for changes in status, and (2) by operator "probability" values, which permit recycling or other alternative paths, and which reflect certain limited mission conditions.

Interaction with an integrated, tutorial control/display system is not explicitly considered, although if the task analysis and OSD work, done before the model is run, were done thoroughly and in detail, the effects upon performance would presumably be accurately represented, at least for simpler systems.

Interaction with the characteristics of the aircraft and control system can be handled in another way in PSM. The model can be tied to a physical aerodynamic simulation, providing more "real" environmental effects, since PSM can operate real-time.

3. Vought WRM. The WRM is sensitive to certain types of mission interaction explicitly. The effect of "time-to-go" upon frequency of check-reading is modeled, on a somewhat intuitive basis, giving an "urgency" effect. The effect of mission requirements and aerodynamics upon control tasks (e.g., frequent corrections to altitude just before a carrier landing) is also explicitly modeled.

The effects of integrated, interactive display/control equipment is not explicitly present, but could be incorporated by means of a sufficiently detailed, valid task analysis, so far as that technique is valid.

4. NADC HOS. The HOS model (with the related HOPROC, HAL and HODAC) is designed to be a flexible, interactive model, hopefully overcoming some of the limitations of the other operator models. Interaction between performance and mission variables (through time-varying priorities and 0-states) and flexibility of procedures (through options such as recalling a reading vs re-reading it) are provided for in the structure of HOS (though not all elements have been constructed in detail.)

5. Boeing CAFES. As indicated earlier in this report, CAFES is an assembly of models, and is designed to incorporate a HOS-like operator model in the future. The existing modules all rely upon detailed task lists and sequence rules as inputs, providing opportunities for modeling interactive systems. Such interactions are not, however, explicitly a part of the CAFES model.

Handling of Color-Coding

The contract statement of work calls for specific attention to the handling of color coding in the models. It appears that none of the models has explicit provision for color effects. However, if performance data (e.g., reading time and error rates) were available for different types of color coding, model runs could be made showing the effects of the color coding changes.

Thus, none of the models has a coding color effect built in, but all of them are capable of showing the effects of color, given adequate input data.

REPRESENTATION OF EQUIPMENT, OPERATOR, AND MISSION DATA IN THREE MODELS

Three of the five models described and compared above are actively being used to represent attack aircraft and crews in complete attack missions.* They are "complete," in a utilitarian sense, and they represent three available, comparable, alternative models for the same classes of mission simulations.

In this section, these three comparable models (Siegel-Wolf, McDonnell Douglas and Vought) are compared on their handling of a number of the rather mundane variables which describe "real" cockpits, people, and missions.

Table 8 is related to equipment characteristics. It will be noted that (1) most characteristics are not "modeled," but must be represented in input data, if at all, and (2) the few characteristics which are represented explicitly vary from model to model.

Table 9 presents a similar comparison related to operator characteristics. The situation here is more complex because some operator characteristics (e.g., fatigue, learning) would be expected to change during the course of the mission. These factors cannot be represented by input data, but must have time-related algorithms associated with them. Other operator characteristics (e.g., reach distance, quickness) would be fixed during a mission, and could be reflected in input data, in the same way as equipment characteristics.

Table 10 is a comparison of the effects of mission characteristics upon the models. Here again, some characteristics (e.g., weather, defense environment) would be time-sensitive, but would presumably be predictably tied to the mission phases and so could be handled as input data effects.

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*The NADC model, HOS, takes a different, more detailed approach to simulation than the other models. It is not efficient to use HOS to simulate an entire mission, but it is complete enough to be considered utilitarian. HOS has been used to simulate the complete hardware/software systems for the LAMPS helicopter operator (ATO) for specific mission segments, and is being used for P-3C applications.

TABLE 8. Comparative Handling of Equipment Characteristics.

Equipment Descriptor	Siegel-Wolf	McDonnell Douglas "PSM"	Vought "WRM"
DISPLAYS			
Distance } Location	I*	E } (2)	E
Direction } Location	I	E } (2)	I
Size	I	I (3)	I
Format	I	I	I
Intensity	I	I (3)	I
Color	I	I	I
Dynamic properties	E**&I(1)	I	I (5)
Content	I	I	I (5)
CONTROLS			
Distance } Location	I	E } (2)	E (6)
Direction } Location	I	E } (2)	I
Size	I	I	I
Type of control	I	I	I
Force required	I	I	I
Type of motion req'd	I	I	I
Accuracy req'd	I	I	I
LIFE SUPPORT			
Seat type/angle	I	I (4)	I
Protective clothing	I	I	I
GENERAL			
Equip.-related time	E (1)	I	I (7)
Equip. failure	I	I	No (8)

* "I" implies that this factor, if represented at all, must be implicit in the input performance data.

** "E" implies that this factor is handled explicitly in the model. Numbered notes indicate how it is done.

NOTES RELATED TO TABLE 8 (EQUIPMENT)

Siegel-Wolf Model

(1) Time required for equipment to function or to cycle is an input; cycle times are then used explicitly as delays where appropriate.

McDonnell Douglas "PSM"

(2) Location is an input for each item by "zone"; performance time is penalized as a function of equipment location.

(3) The model will output a minimum size and luminance for displayed data, as a function of G-load, etc.

(4) Seat angle is an input, but can be changed (15° or 65°) and will affect performance.

Vought Model

(5) The Vought WRM explicitly models these factors in the "continuous" task model, but not the "discrete" one.

(6) Reach times are computed by an algorithm which reflects control locations. Penalties may also be assessed against "action" time, for long reaches.

(7) Equipment time delays could be included in empirically determined task times.

(8) For discrete tasks, probability of correct performance (which could include equipment failures) is not used.

TABLE 9. Comparative Handling of Operator Characteristics.

Operator Descriptor	Siegel-Wolf	McDonnell Douglas "PSM"	Vought "WRM"
PHYSICAL			
Size	I*	I	I
Somatotype	I	I	I
Posture	I	E(10)	I&E(18)
Physical Stress	I	E(11)	I&E(19)
Visual functioning	No	I&E(12)	I&E(19)
BEHAVIORAL			
Proficiency	E**&I(1)	I	I
Attention	I(2)	I(13)	No
Fatigue	No(3)	I(13)	No
Psychol. Stress	E(4)	I(13)	No
Errors/Accuracy	E&I(5)	E&I(14)	No(20)
Morale/Aspiration	E(6)	I or No (13)	No
Time per action	E&I(7)	I(15)	I/E(21)
SOCIAL			
Crew Makeup	I	I(16)	I
Cohesiveness	E(8)	I/E(17)	No
Communication	E(9)	I(16)	I

* "I" implies that this factor, if represented at all, must be implicit in the input performance data.

** "E" implies that this factor is handled explicitly in the model. Numbered notes indicate how it is done.

NOTES RELATED TO TABLE 9 (OPERATOR)

Siegel-Wolf Model

(1) Individual "speed" factor is an input; performance is modified by explicit algorithms related to stress, aspiration level, goal proximity.

(2) Variations in "attention" are implied as an effect of stress, goal proximity.

(3) Performance changes due to fatigue during mission are not included.

(4) Stress is a central concept in U/DOSM model. Computed as f (time remaining, stress threshold, task type).

(5) Average error rate an input; pass/fail on a specific run is a random draw.

(6) "Aspiration level" is computed continually as function of past performance, stress, etc.

(7) Mean and standard deviation of expected task times are input; random draws from a truncated distribution generate the specific task time on a given run.

(8) "Cohesiveness" of a 2-man crew is computed continually as a function of stress levels of each member.

(9) Performance on "communication" subtasks handled like other tasks; an algorithm for time as a function of message size is used.

McDonnell Douglas "PSM"

(10) Seat back angle (15° to 65°) modifies performance; previous eye or hand position modifies task times.

(11) G-load is computed continually; an algorithm modifies performance time with G. Also, see note (13).

(12) An input pattern plus current estimates of head orientation define the geometry of the visual field, as a function of posture and point of regard; used for search time estimation. Also, dark adaptation as a function of time is modeled explicitly.

(13) Several "environmental stress" factors exist as inputs, and can be varied from task to task through the mission. They might be used for factors not now considered.

(14) Basic performance accuracy is an input by task; a "learning curve" can modify performance during the mission.

(15) Basic performance time is input as a simplified distribution, by display/control; random draws are made to obtain specific times.

(16) "PSM" is a multi-man model; crew make-up and intra-crew communication can be handled, via input data.

(17) "Cohesiveness" is an identified input; modifiable during the mission.

Vought "WRM"

(18) General posture is not considered; hand or foot position at the end of a task affects the next reach-time explicitly.

(19) Penalties are applied for a high-G condition; other physical stresses are considered if time decrements can be determined.

(20) Accuracy of performance on continuous tasks is modeled, but is not part of this evaluation.

(21) Median time per task is an input; modifications for reach distance are explicit (see note 18).

TABLE 10. Comparative Handling of Mission Characteristics.

Mission Descriptor	Siegel-Wolf	McDonnell Douglas "PSM"	Vought "WRM"
IDENTIFICATION			
Mission type	I*	I	I
Difficulty	I(1)	E(4)	I
Criticality	I(1)	E(4)	I&E(9)
TIME CONSTRAINTS			
Total time available	I	I	I
Event sequence	I&E(2)	I&E(5)	I&E(9)
Event time limits	I&E(2)	I&E(5)	I&E(10)
ENVIRONMENT			
Terrain		I(6)	I
Weather	I(3)	I(6)	I
Defenses	I(3)	I(6)	I
ECM	I(3)	I(6)	I
Flight regime	I(3)	E(7)	E(11)
Maneuvers/G-loads		E(8)	E(12)

* "I" implies that this factor, if represented at all, must be implicit in the input performance data.

** "E" implies that this factor is handled explicitly in the model. Numbered notes indicate how it is done.

NOTES RELATED TO TABLE 10 (MISSION)

Siegel-Wolf Model

(1) These characteristics would be reflected only in the "available time" and "essentiality" inputs.

(2) Subtask sequence and time are input, but also subject to modification during a run as a function of "random draw" variation in performance time and consequent time stress; non-essential tasks can drop out.

(3) None of these factors is input per se; they could affect performance time and accuracy inputs, and task sequence and essentiality.

McDonnell Douglas "PSM"

(4) "Criticality" and "Difficulty" are input for each task; allowable values are 1 to 4 (criticality) and 1 to 3 (difficulty). These values will affect the way the simulation runs.

(5) Event times and sequence - see note (2).

(6) Values of "stress," "altitude," "temperature," factors can be entered at each task; they could reflect these environmental characteristics.

(7) "Altitude" and "temperature" are input; they are used in computing maneuver envelopes, etc.

(8) Predicted G-loads are used, with algorithms in the model, to modify sensory and motor task performance.

Vought "WRM"

(9) "Criticality" is an input for each task; sequencing of tasks is based partly on this value.

(10) Event time and sequence - see note (2).

(11) Flight regime is modeled explicitly in the "continuous" portion of the model; workload for all tasks is affected.

(12) Above a threshold level, performance decrements are assessed.

CONCLUSIONS AND RECOMMENDATIONS

SUMMARY OF MODELING WORK

The review presented in this report leads to a number of conclusions and generalizations concerning crew/cockpit modeling efforts. They are stated briefly here. It must be reiterated that the sheer volume and complexity of the model documentation, and the fluidity of most of the models, make any generalizations somewhat risky. It cannot be too strongly stated that anyone seriously contemplating substantial work in this kind of modeling should study the original documentation before making choices and decisions.

Two Modeling Approaches

The apparent motivation behind the development of the McDonnell and Vought models (and to a lesser extent the Siegel-Wolf models) was to get a good, dynamic representation of the man-machine system "on line" at as early a date as practical. This has been accomplished with considerable success.

The apparent motivation behind Wheery's effort (the HOS complex) and perhaps the Boeing CAFES and Air Force SAINT work as well, has been to develop a framework with enough depth, breadth and flexibility to handle a wide variety of present and future modeling needs. This kind of effort is, by its nature, somewhat open-ended; consequently, it is almost impertinent to ever expect such a model (or collection of models) to be "completed." The ground covered during the development of the models, however, gives rise to a variety of important questions concerning the nature of the man/machine system. These questions must be faced if a deeper understanding of the system is to be achieved.

The Importance of Analysis

None of the models takes the place of careful, detailed scenario development and task analysis. Indeed, the required model inputs force the analyst to work through mission and system options in considerable depth.

The Importance of Performance Data

With the exception of the Siegel-Wolf information theoretic work for Apollo, all the models depend exclusively on performance data for the basic task times and accuracies. In addition, the form of the "corrections" and "penalties" which are imposed by the models to account for G-load, stress, cockpit layout, etc., must be validated against performance data if they are to be used with confidence. In some cases, validation presents a truly formidable task, since it involves factors (such as fatigue, level of aspiration, time stress) which are notoriously difficult to measure singly, let alone in combination.

The Elusiveness of Interactive Control

The paradigm lying behind the modeling of cockpit operations is generally task-oriented. The operator senses a condition, processes the information, and acts on the system, in sequence. Some parallel tasks are permitted, and branching is accommodated, but the basic stimulus - response structure is dominant. Whether this structure is sufficiently flexible to represent adequately the kind of "supervisory control" which is envisioned for future attack aircraft remains an open question.

RECOMMENDATIONS

The practicability of computer modeling of the cockpit/crew system in attack aircraft has been adequately demonstrated. Gradual development of the existing models continues, but the basic structures and related software realizations appear to be well matured.

The major areas requiring new or increased work appear to this reviewer to be two:

1. Improvements are needed in the formulation and validation of the modifiers, penalties, and corrections which have been involved to bridge the gap between laboratory or simulator data on human performance and the "real world" of combat aviation. All of the models incorporate some of these effects, often on the basis of intuitive sub-models, but the relative importance of different effects, and their interactions in real-world settings, remains elusive.

2. Careful study of the operator role in proposed advanced, integrated, interactive, highly automated systems needs to be undertaken. The NATO Conference report cited in the Introduction is an indication that this effort is indeed under way.